NPS-PH-05-001

NAVAL POSTGRADUATE SCHOOL
Monterey, California

Jefferson Lab Free Electron Laser
10 kW Upgrade - Lessons Learned

by

B. W. Williams

May 2005

Approved for public release; distribution is unlimited.

Prepared for: Naval Postgraduate School
Monterey, CA 93943-5000

NAVAL POSTGRADUATE SCHOOL
Monterey, California 93943-5000

This report was prepared for Naval Directed Energy Weapons Program Office (PMS-405) and funded by PMS-405 and Naval Postgraduate School.

This report was prepared by:

Brett Williams
LT USNR

Reviewed by:

James H. Luscombe
Chairman
Department of Physics

Released by:

Leonard A. Ferrari, Ph.D.
Associate Provost and
Dean of Research

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE May 2005	3. REPORT TYPE AND DATES COVERED Technical Report

4. TITLE AND SUBTITLE JLAB FREE ELECTRON LASER 10 KW UPGRADE - LESSONS LEARNED	5. FUNDING NUMBERS RPH43
6. AUTHORS Williams, Brett	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey CA 93943-5000	8. PERFORMING ORGANIZATION REPORT NUMBER NPS-PH-05-001
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Directed Energy Weapons Program Office (PMS-405)	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT(*maximum 200 words*)

The activities of the Free Electron Laser (FEL) Group at Thomas Jefferson National Accelerator Facility (JLab) in Newport News, Virginia, during the Infrared Demonstration Free Electron Laser Upgrade Project are summarized. The project spanned four years, from July 2000 to June 2004, and resulted in the upgrade from a 1 kW-class FEL to a 10 kW-class FEL at JLab. Lessons learned during the Upgrade are presented and discussed.

14. SUBJECT TERMS Free Electron Lasers, Jefferson Lab	15. NUMBER OF PAGES 23
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

Executive Summary

This report summarizes the activities of the Free Electron Laser (FEL) Group at Thomas Jefferson National Accelerator Facility (JLab) in Newport News, Virginia, during the Infrared Demonstration Free Electron Laser Upgrade Project. The project spanned four years, from July 2000 to June 2004, and resulted in the upgrade from a 1 kW-class FEL to a 10 kW-class FEL at JLab. The primary purpose of this report is to present lessons learned during the Upgrade. While there is some discussion of budget and management issues, it is only as they relate to the technical aspects of the project, the impact of technical decisions on budget having been deemed an important lesson learned.

In preparing this report, an attempt was made to interview as many members as possible of the JLab FEL group and the Review Panel assembled to oversee the project for the Office of Naval Research (ONR). More than fifty hours of interviews yielded a great deal of helpful information and insights, including detailed technical data not readily evinced from more than 2000 pages of weekly reports and other publications.

The interviews were also useful in bringing into relief overall impressions of the project. A general sense of teamwork between JLab and the Panel marked many of the comments, particularly in reference to the biggest challenges to the project, and JLab personnel repeatedly and almost unanimously remarked on the value of relationships with individual panel members. Individuals also noted the essential leadership role played by PMS-405, remarking that the project benefitted from the existence of a program office dedicated to directed energy weapons research.

Some of the lessons learned are general and programmatic, for example:

- a 25% contingency in a project's research budget is critical and should be funded;
- it is important for a laboratory to seek and/or accept outside help when needed;
- latitude must be given a scientific project to explore areas not obviously connected to programmatic goals;

some are detailed technical lessons, for example:

- aggressive and comprehensive computer modeling of an electron beam transport system is essential;
- it is advisable to perform one's own metrology on procured optics, regardless of vendors' specifications;
- optical cavity losses must be identified and dealt with in high power lasers.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Free Electron Laser

In 1972 Stanford physicist John Madey proposed the development of a coherent light source based on the radiation emitted by accelerating relativistic free electrons: a free electron laser. In 1976, his team amplified a CO_2 laser beam using relativistic free electrons from the Stanford Superconducting Linear Accelerator. They later observed coherent infrared radiation at a wavelength of 3 μm using the accelerator in an oscillator configuration. These achievements gave birth to the contemporary free electron laser described below.[1]

System

The two main components of a free electron laser are an *accelerator* which imparts kinetic energy to a beam of free electrons, and an *undulator* which extracts energy from the beam in the form of coherent radiation. There are a variety of FEL designs; all contain these two essential elements. Varying among individual configurations are the methods by which the electron beam is created, transported, then dumped, and how the radiation is amplified. Some FEL's are amplifiers, some are oscillators.

The oscillator configuration is shown in Figure 1.1. Electromagnetic radiation is recirculated within a resonant cavity, and the increased optical power is outcoupled through a partially-silvered mirror. In the amplifier configuration (Figure 1.2), spontaneously emitted light (or light from a seed laser) is amplified in a single pass through the undulating electron beam.

[1] This section is from Chapter One of B. W. Williams, "Hermite- and Laguerre-Gaussian Modes in Free Electron Lasers", Naval Postgraduate School masters thesis, Naval Postgraduate School, Monterey, CA, (expected) September 2005.

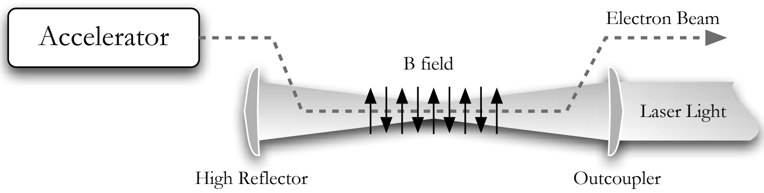

Figure 1.1: Oscillator FEL

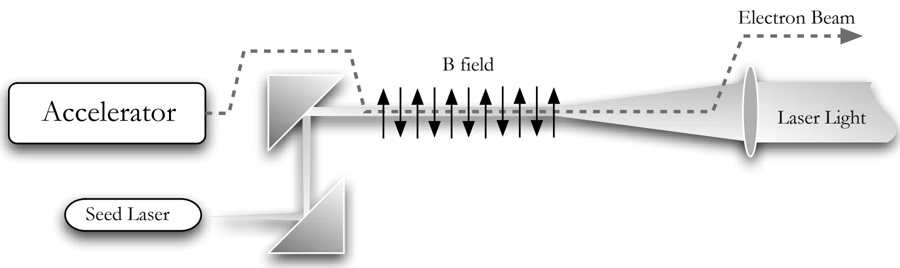

Figure 1.2: Amplifier FEL

The source of energetic electrons is usually a cathode within an electron gun. Whether configured as an oscillator or amplifier, the electron beam itself may be either recirculated or dumped after exiting the undulator. Recirculation allows the recovery of beam energy back to the accelerator and the benefit of dumping less energetic electrons. In the RF recovery configuration, electrons return to the accelerator 180° out of phase with respect to those entering from the beam source. Figure 1.3 shows the entire system for a recirculating free electron laser oscillator.

Attributes

The free electron laser's most striking difference from conventional lasers is also its chief advantage. The absence of a vulnerable medium such as a crystal or fluid chemical matrix means that an FEL can achieve extremely high intensity without damaging the laser itself. High wall-plug efficiency (∼10%) is predicted for high power FEL's. Reliability is also a characteristic: currently operating FELs run continuously and reliably for weeks.

Free electron lasers are continuously tunable. The relativistic Lorentz factor γ of the pulsed electron beam and the undulator period λ_0 and undulator RMS magnetic field strength $B_{\rm rms}$ determine the laser wavelength λ according to

$$\lambda = \frac{\lambda_0(1+K^2)}{2\gamma^2}. \tag{1.1}$$

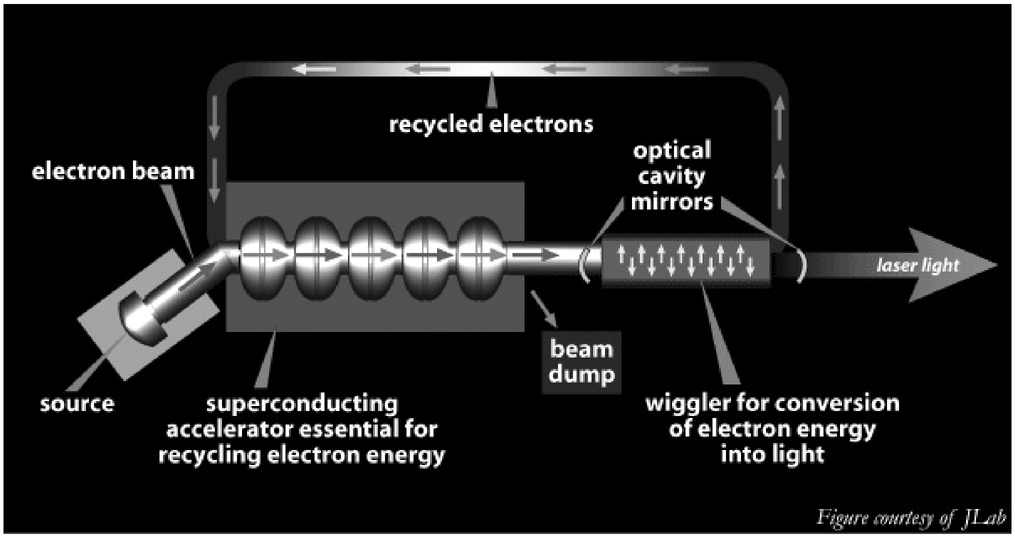

Figure 1.3: Recirculating free electron laser oscillator.

where the undulator parameter K is defined as

$$K = \frac{eB_{\rm rms}\lambda_0}{2\pi mc^2}, \tag{1.2}$$

e is the electron charge, m the mass of the electron, and c the speed of light in vacuum. The relation (1.1) suggests that the undulator wavelength and magnetic field as well as the energy of the electrons[2] may be adjusted within an operating laser to yield light over a range of wavelengths. Free electron lasers have been designed to produce radiation from microwaves to X-rays, and they are continuously tunable over a smaller range within these regimes. In addition, the short-pulse nature of the radiation may enhance propagation of optical power through the atmosphere, making the laser particularly suited as a weapon. At the present time, the price for such desirable traits is a large and expensive machine.

1.2 Thomas Jefferson National Accelerator Facility

The facility destined to become the Thomas Jefferson National Accelerator Facility (TJNAF, hereinafter Jefferson Lab or JLab) was first conceived in the 1970's as a high energy physics research facility. Planned by the Southern University Research Association (SURA), its goal was to capture funds earmarked by the Department of Energy (DoE) to help establish a "strong base for nuclear physics research in the Southeast".[3]

[2]Tuning via electron beam energy is generally considered more difficult than via undulator geometry. Indeed, significant changes in electron energy require adjustments to guiding and focusing magnets along the entire length of the accelerator.

[3]Southern University Research Association website: www.sura.org.

The SURA proposal, initially in competition with proposals from Massachusetts Institute of Technology, University of Illinois, Argonne National Laboratory, and the National Bureau of Standards, was selected in 1983. In 1987 in Newport News, Virginia, construction began on the world's first large-scale superconducting electron accelerator: the Continuous Electron Beam Accelerator Facility (CEBAF). The first experiments began in the mid 1990's taking advantage of electron energies as high as 4 GeV. In 1996, CEBAF was officially renamed the Thomas Jefferson National Accelerator Facility, although the machine known as CEBAF is still the main device at the facility.

Chapter 2

History of the JLab FEL

The following history of the Navy's interest in high energy lasers (HEL) is graciously provided by John Albertine, former director of PMS-405, the Navy's directed energy weapons program office.

> The first laser type which was scaled to high power (relative to Navy weapon needs), was a combustion driven CO_2 laser which lased on one of a few lines between 9.8 and 10.6 μm. This occurred in the 1960's and early 1970's. These devices were used by the Navy for materials interaction tests, component development, and beam control and propagation experiments. From an atmospheric scattering standpoint, this was a good wavelength for maritime propagation but it was quickly learned that molecular water absorption was high enough to make thermal blooming a serious problem for self defense or escort scenario applications.
>
> A new combustion driven laser technology was developed in the early to mid 1970's which offered potential for improvement. The deuterium fluoride (DF) laser was scaled to high power with work funded by the Defense Advanced Research Projects Agency (DARPA) and the Navy at Aerospace Corporation, Navy Research Laboratory (NRL), TRW, and a few other places. These devices lased simultaneously on a half-dozen lines between 3.6 and 4.0 μm and were commonly described as lasing at 3.8 μm. A series of experiments, called Unified Navy Field Test Program (UNFTP), were run at TRW (San Juan Capistrano test site) in 1977 and '78. These combined the sub-MW class NaCl laser with the Navy Pointer Tracker (NPT) beam director to provide the Navy's first integrated HEL test bed. The tests were quite successful and shot down Army tube-launched, optically tracked, wire-guided (TOW) missiles in crossing engagements. This encouraged the Navy to proceed with DF technology.
>
> The Navy then built the MW-class Mid-Infrared Advanced Chemical Laser (MIRACL) and the SeaLite Beam Director (SLBD) beam director. These were to provide full-scale performance for Navy weapon needs although using experimental hardware. This system was integrated at the White Sands Missile Range HEL System Test Facility (HELSTF) and successfully tested between the mid-1980's and about 1992. Subsonic and supersonic missiles were shot down in crossing engagements.

> During this same time period, the Cold War ended and the Navy's interest shifted to littoral operations that required an emphasis on self defense instead of escort defense. This resulted in a new series experiments at HELSTF that emphasized self-defense (low or no slew rate) scenarios. Propagation tests were conducted as well as some self-defense tests against cruise missile surrogates. The results of these tests clearly demonstrated that the DF laser wavelength, while useful for escort defense scenarios, exhibited too high atmospheric absorption for self-defense.
>
> We then conducted a series of Wavelength Selection Studies whose purpose was to identify any wavelengths that had low enough absorption to be useful for Navy self-defense. A few narrow wavelength region candidates were identified around 1, 1.6, and 2.2 μm. No scalable chemical lasers were available at these wavelengths. While the 1 μm wavelength could be reached with a solid state laser, it was felt that achieving MW power level was a long way off.
>
> Through process of elimination, the free electron laser became the only viable candidate. Although it had only achieved 10 W of average power, much time and money had been spent during the Strategic Defense Initiative (SDI) era to investigate power scaling. Professor [William] Colson [of NPS], whom I had known for years and worked with, encouraged the conclusion that FEL's should be considered.[1]

2.1 The IR Demo (1 kW)

Eager to find additional uses for their very successful and highly efficient cryogenic radio frequency electron accelerator technology, by the mid-1990's JLab had already been considering building a free electron laser for years. While money had been obtained from DoE and the Commonwealth of Virginia to develop a photo-injector for a FEL, funds for the construction of a new facility were contingent on matching federal funds. To get that money, JLab needed a reason to build a high power FEL.

That reason came in the form of the Navy's HEL program. A meeting between JLab director Hermann Grunder and John Albertine confirmed that the needs of the two programs were highly compatible.

> Not long after we reached the conclusion that an FEL was the only identifiable solution to the Navy's problem, Professor Colson introduced me to Dr. Hermann Grunder who was the director of CEBAF (now called JLab). They had support from their local congressman to build an FEL there at the lab but needed a government partner. Their interest was in building a multi-kW UV FEL for experimental purposes. I became convinced that elements of the basic JLab concept (which included SRF beam acceleration and energy recovery) were key to the efficiency and compactness of any ultimate Navy system and so I was interested in pursuing the development at JLab. Hermann and I struck a deal that I would support this development within the Navy and try to

[1] J. Albertine, memorandum to the author, 7 April, 2005.

> convince Dr. Eli Zimet at ONR to accept the congressional funds if JLab would agree to initially develop a kW class IR (not UV) laser.[2]

In the fall of 1996, Congressman Herb Bateman (R, VA) introduced the following language, subsequently added by Congress, to the 1996 Defense Authorization Act:

> Sec. 217 - Development of Laser Program. The amount authorized for appropriation by section 201 is hereby increased by $9,000,000, to be used for the development by the Navy High Energy Laser Office of a continuous wave, superconducting radio frequency free electron laser program.[3]

The JLab Free Electron Laser was born.

In June of 1998, the JLab Infrared Demonstration Free Electron Laser (IR Demo) achieved first light with 155 W average power, almost 30 times the existing power record for a FEL. By July it was up to 311 W. In March of 1999, JLab began lasing with energy recovery, the optical power now over 700 W, and on 15 July, 1999, the FEL exceeded its design goal of 1 kW by producing 1720 W of infrared light. For perspective, Table 2.1 compares the JLab laser at that time to a notional weapon-class laser. As John Albertine suggested, there was still a long way to go. But JLab had demonstrated the ability to meet requirements and deliver a good machine at a reasonable price. It was enough for the Office of Naval Research (ONR) to provide JLab with another $9 million to begin developing a 10 kW upgrade to the existing FEL.

Table 2.1: Comparison of Original JLab FEL with Weapon Grade FEL

	JLab FEL (June 2000)	Weapon FEL (Notional)
Average Power	1.7 kW	1 MW
Average Current	5 mA	900 mA
Beam Energy	48 MeV	100 MeV
Bunch Charge	60 pC	1800 pC
Peak Current	60 A	600 A
Beam Radius	100 μm	300 μm
Pulse Length	0.4 ps	3 ps
Pulse Repetition Rate	$\sim$ 50 MHz	$\sim$ 500 MHz
Optical Wavelength	3-6 μm	1 μm

Parameters for 1 kW laser are from R. D. McGinnis, et al, "Free Electron Laser Material Damage Studies", Naval Postgraduate School technical report NPS-PH-01-001, November 2000. Figures for megawatt class free electron laser are proposed.

[2] *Ibid.*

[3] 1996 DoD Appropriations Act, Public Law 104-106.

Lessons Learned

The IR Demo showed that an FEL could be scaled from 10 W to 1 kW. Both ONR Review Panel members and JLab staff expressed disappointment that the 1 kW machine was not allowed to operate longer: to use it as a physics test bed to “better anchor our codes and to work the engineering problems”, and to extend operations in the user facility.

2.2 IR Upgrade (10 kW)

The JLab IR Demo FEL Upgrade project officially began on 1 June, 2000. At that time the JLab FEL was routinely lasing with an average power of 1500 W at 6 μm, and at varying powers over a range of wavelengths from 3 to 6.2 μm.[4] To achieve 10 kW, JLab proposed:[5]

- doubling the injected current from 5 to 10 mA by increasing the bunch charge from 67 to 135 pC;
- installing two additional cryomodules to raise the beam energy to ~160 MeV;
- upgrading the recirculator to accommodate higher beam energy and a new FEL insertion embedded in the machine backleg;[6]
- using a new 32 meter long optical cavity designed for high power.

Table 2.2: Projected Parameters for FEL Upgrade as of August, 2000

	IR Demo	Upgrade
Optical Power (kW)	1	10
Wavelength Range (μm)	3-6.2	2-10
Bunch Charge (pC)	67	135
Average Current (mA)	5	10
Beam Energy (MeV)	40	160

Source: see footnotes 4 and 5.

[4] Historical parameters of JLab 1 kW IR Demo FEL are from Project history on JLab Website, http://www.jlab.org/FEL, 2005; and Private Communication, G. Neil, 17 March, 2005.

[5] Nominal parameters for JLab 10 kW IR Demo Upgrade are from D. Douglas, “The Jefferson Lab 1 kW IR FEL”, *Proceedings: XX International Linac Conference*, Monterey, California, 2000, p.720. In this paper, JLab physicist Dave Douglas summarizes the Phase 2 details as outlined in the SOW enclosed in the December 2000 MOA.

[6] In the IR Demo, the undulator was located just downstream of the linac. In the Upgrade it would be moved to the backleg of the recirculating beamline (see Figure 3.2).

Table 2.2 summarizes the parameters of the IR Demo and those planned for the Upgrade. The parameters show that JLab already had a 200 kW electron beam:

$$\begin{aligned} P &= IV \\ &= 5\,\mathrm{mA} \times 40\,\mathrm{MeV} \\ &= 200\,\mathrm{kW}, \end{aligned}$$

but based on their modeling of the FEL, JLab supposed that the maximum possible extraction was 2%, that would give 4 kW optical power.

The upgrade would be broken into two phases: Phase 1 would focus on the development of the necessary technologies for the upgrade. Phase 2 would incorporate those technologies, culminating in the commissioning of a 10 kW free electron laser. The proposed schedule for Phase 2 was outlined in the Memorandum of Agreement (MOA) between the DoE and ONR, and is summarized in Table 2.3. According to the MOA, the first components were to be installed in April of 2002.

Table 2.3: Proposed Top Level Schedule for Phase 2 (December, 2000)

Milestone	Date
Project Start	March 01
Cryomodule No. 2 Installed	April 02
Wiggler Installed	April 02
Optical Cavity Installed	July 02
Cryomodule No. 3 Installed	July 02
Installation Complete	October 02

Source: Memorandum of Agreement between Manager, Oak Ridge Operations Office, U.S. Department of Energy and Office of Naval Research, Enclosure (1) JLab Statement of Work - IR FEL Demo Upgrade Project, Revision 3, December, 2000.

The JLab FEL building includes a number of user labs into which FEL light is transported for use in experiments. The FEL team continued to operate the laser in support of user operations as initial preparations and fabrications were conducted and vendors were contacted for new components. Improvements were made on the existing laser, which continued to operate through November of 2001, achieving as high as 2.1 kW average power (twice the original design specification) during user and test runs, expanding the operational range to 1-6.2 μm, and producing more than 70 scientific publications. The facility demonstrated 94% up time during user operations supporting, for example, 170 hours of JTO lethality experiments in 2001.[7] A number of power records were broken at various wavelengths, and a decades-old

[7] For more on user applications during this time period, see H. F. Dylla, "Jefferson Lab's FEL Gets Down to Business", *Laser Focus World*, August 2001.

prediction regarding even-harmonic FEL lasing[8] was experimentally demonstrated when the second harmonic was observed in January of 2001.

As the FEL was "tweaked" in the months leading up to decommissioning of the 1 kW configuration, the continued operation of the laser in support of user applications proved extremely useful. Leaving the machine in a given operational condition for extended periods helped to identify problem areas, and as the power was increased to 2 kW, lessons learned about optical transport were directly applicable to efforts towards the 10 kW machine.

A significant development during this time concerned the production of THz radiation, a by-product of magnetically steering the short bunches of electrons within the beam transport system. Light at these wavelengths (0.1 - 1.0 mm) is important to science and industry, and in November of 2001, JLab demonstrated the ability to deliver 100 W of broadband THz radiation—100,000 times the intensity of traditional sources. THz radiation may eventually be a great boon to the user facility, but the reason it was being monitored in the first place was that while non-ionizing, these wavelengths can transfer heat to sensitive components. The resonator outcoupler would prove to be especially at risk to heating due to its location downstream from the first reverse bend dipole magnet.[9]

On 8 November at a semiannual review meeting, JLab presented a status report citing completion of Phase 1 elements of the upgrade. The scope of this phase, as defined by the 2000 MOA, had been the development of "key technologies to extend FEL output power to beyond 10 kW", and the status of upgrade deliverables was presented (Table 2.4). On 18 November, decommissioning and disassembly of the IR Demo FEL began.

Table 2.4: Upgrade Deliverables Status as of 8 November, 2001

Deliverable	Status
Complete design for 10 kW FEL	Complete
RF power for injector upgrade [two 100 kW klystrons]	Complete
RF power system for 2 cryomodules [sixteen 6 kW klystrons]	Complete
High power (10 kW) IR wiggler for 2-10 μm	Complete
Electron gun power supply upgrade to 10 mA	Design complete
Prototype high power (10 kW) optical cavity	Design complete
Component tests for beam transport at 200 MeV	Design complete
SRF improvements to handle 10 mA and improved gradients	Design complete

Source: F. Dylla, "FEL Upgrade Project Status Report for DoE/DoD Semi-Annual Review", presented at semiannual review meeting, Thomas Jefferson National Accelerator Facility, Newport News, VA, 8 November, 2001.

[8] W. B. Colson, G. Dattoli, and F. Ciocci, "Angular Gain Spectrum of Free Electron Lasers", *Physical Review*, Vol. 31, No. 2, 1984.

[9] See Figure 3.7. The problem was ultimately remedied by swapping the high reflector and outcoupler. This is discussed in further detail in Section 3.3.

Phase 1 ended with $1.3 million in cost and schedule variance. The main contributor to the variance was the beam transport system, reflecting the expense inherent in developing such a robust beam transport lattice and the problems that tend to plague large scientific experiments in procuring small (not mass-produced) quantities of high quality components. The magnet lattice, designed to operate over the broad energy range of 80-210 MeV, called for two dozen spectrometer-grade electromagnets of varying geometries. The Review Panel commented specifically:

> The work is of highest quality, every effort was made to reuse designs, and two vendors were hired to assist. However, the large number of components and their tight tolerances have resulted in all but $100K of the budget being spent and $700K of unaccomplished work being transferred into [Phase 2] for a total of [more than] $2M of remaining work.[10]

At the 8 November meeting, JLab reported that a "major fraction of [the] Phase 2 effort [had been] deferred until the completion of Phase 1 scope and cost". Proposed phase 2 deliverables included:

- Install and test high power RF system in injector and cryomodules 2 and 3.
- Install and test gun HV power supply and other gun improvements.
- Construct, install, and test 3rd cryomodule; install and test 2nd cryomodule.
- Install and test high power wiggler.
- Install and test optical system.
- Install and test 200 MeV transport system.
- Upgrade control and diagnostic systems.

With the receipt of $2.6 million in Navy and JTO funds in February of 2002, JLab embarked on the above list. The next 12 months was to become a period marked by setbacks and subsequent innovations, and ultimately some compromises.

Testing and simulations on the third cryomodule indicated that the unit could not deliver the required beam quality at the high currents necessary for 10 kW lasing. The beam breakup threshold[11] of the cryomodule was predicted to be 3 mA, while the FEL electron beam was to run at 10 mA. This issue led to discussions about trying to obtain 10 kW at longer wavelengths, which would require only two cryomodules. For example: with an 80 MeV

[10] J. Albertine, Memorandum: "Summary of FEL 10 kW Upgrade Phase I Closeout Meeting at Jefferson Lab on November 8 & 9", to Dr. Eli Zimet, ONR-35, 17 December, 2001.

[11] Beam break-up is discussed in §3.2.

electron beam, the optical klystron undulator JLab was using would be able to deliver 10 kW at no shorter than 6 μm wavelength. The optical klystron, donated to JLab by Northrop Grumman, has a rather long period ($\lambda_0 \sim 20$ cm) by FEL standards. While funds had been identified to study the design of the optimum undulator, actually building (or buying) it was not yet in the budget. Absent a shorter-period undulator, a higher energy beam, and thus the third cryomodule, was required for 10 kW lasing at 1 μm.

Meanwhile, the electron gun[12] suffered a series of breakdowns due to arcing, a result of conditioning at very high voltages. Acknowledging that it was not necessary for 10 kW lasing, JLab was eager to demonstrate a 500 kV electron gun: a first of its kind, and a necessary step towards >1 kW UV and ultimately >100 kW IR lasing. Ultimately, the panel recommended limiting operation of the electron gun to 350 kV for fear of compromising internal components which might lead to schedule slip.

While the above led to schedule variances, it was once again the beam transport system that was identified as having "consumed a noticeable portion of the commissioning funds".[13] At this point, the procurement of some higher order magnets had to be deferred. Phase 2 of the 10 kW upgrade program officially ended on 30 September, 2002, but by November, all funds allocated for commissioning had been spent.

By February, 2003, the FEL was configured for first light, but the scheduled end-date of commissioning had to be extended from 31 March to 30 September. The Office of Naval Research provided \$3.8 million of FY03 funds to cover the cost increases and technical difficulties. In May electron beam operations began, and on 12 June spontaneous emission at 6 μm was achieved. On 20 June the FEL lased from 5.5-6.6 μm at low power with no energy recovery.

In July, JLab shut down the laser to reconfigure for high power. They were back on line by the end of the month and in August achieved CW lasing at 6 μm with energy recovery, but with some problems. Mounting issues had developed with the 6 μm optics. Ten micron optics, also being considered as a candidate for high power lasing in the two-cryomodule configuration, were absorbing too much power. Also, there was something wrong with the longitudinal phase profile of the electron bunches, evident in low gain from the undulator. Simulations suggested that either the electron bunches were too long, not providing sufficient peak current, or too short with too large an energy spread for high power lasing. Simulations were employed to answer this question, but investigations using the laser would have to wait: a significant delay was about to occur, completely beyond anyone's control.

In mid-September 2003, a category five hurricane, Isabel, approached the coast of North Carolina with 150 knot winds. It made landfall on 18 September and proceeded on to West Virginia. By the time it dissipated, 34 people were dead and \$3.4 billion in damage had

[12]The electron injector is discussed in §3.1.

[13]J. Albertine, Memorandum: "Summary of FEL 10 kW Upgrade FEL Program Review Meeting at Jefferson Lab on November 20 & 21", to Mr. Gil Graff & CDR Roger McGinnis, USN, 28 January, 2003.

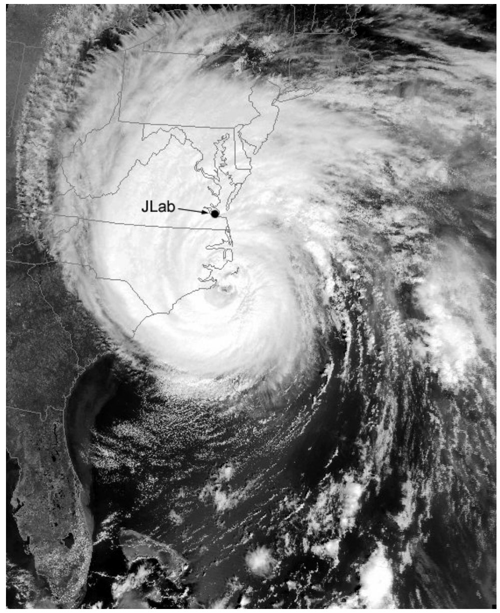

Figure 2.1: Hurricane Isabel struck the Eastern Seaboard on 18 September with 100 knot winds.

been done to property as far north as New York and as far west as Ohio. The impact on Jefferson Lab is described in the text of the weekly brief for that period:

> The main impact of the storm on both FEL and CEBAF operations will be due to the extended loss of site AC power. Site power was not restored until late Sunday afternoon despite JLab being located on two major trunk lines from the Surry and Yorktown power plants. We do not have sufficient emergency power generation on site to keep our main helium refrigerator on line (approx. 8 MW). We can last 1-2 days before the cryomodules start warming up and venting helium. By Sunday all 42 modules in CEBAF and the 2 linac modules (and injector unit) in the FEL were near room temperature with the helium inventory vented. The Cryogenic and SRF groups have assembled a recovery plan. A period of approximately a month is required before we replace the 65,000 liter liquid helium inventory and all the modules are cooled back to the operational temperature of 2 K.[14]

The FEL team made the best of the unexpected shutdown, working on outstanding beamline issues. By the end of October, the helium supply had been replenished, having been trucked in piecemeal, and the FEL cryomodules were cooled down to 2 K. As a testament to the quality of the JLab accelerator cavities, some of the CEBAF cryomodules had not been to room temperature in almost a decade, and yet there were no failures upon re-cooling. In November, a vacuum leak in the warm window of the first cryomodule set back commissioning

[14] F. Dylla, “FEL Upgrade Project Weekly Brief - September 22-26, 2003”, memorandum to distribution, 26 September, 2003.

one week, but later that month, 700 W lasing at 10.1 μm marked the essentially full recovery from the effects of the hurricane.

Everything was in place for 10 kW lasing, though not at 1 μm. But continued problems with optics prevented high power lasing, and during the January 2004 semiannual review, JLab claimed:

> If we had 6 or 10 micron optics that met our absorption specs (100 ppm), *as we had in place for our 3-6 micron lasing with the IR Demo* [his emphasis], then we would be lasing at $\sim$ 10 kW with the achieved parameters of the present FEL configuration.[15]

In fact, losses in the 10 μm optics were as high as 7000 ppm. However, the injector was working well, accelerator commissioning had progressed rapidly, and progress had been made in achieving design specifications, as shown in Table 2.5.

Table 2.5: FEL Upgrade Design vs. Achieved Specifications, January 2004

Driver Accelerator	Design Spec.	Achieved
Linac Energy (MeV)	80	80
Linac Average Current (mA)	10	7.0
Bunch Charge (pC)	135	150
Transverse Emittance (mm-mrad)	30	15
Energy Spread (%)	0.3	0.3
Bunch Length (ps)	0.5	$\sim$0.8
FEL System		
Average Power (kW)	10	$\sim$1
Pulsed Power (kW)	N/A	2.5
Lasing Efficiency (kW/mA)	$\sim$1	$\sim$1 (pulsed)

Source: F. Dylla, "FEL Upgrade Project Overview Report for DoE/DoD Semi-Annual Review", presentation at 10 kW FEL Program Review, 29-30 January, 2004.

In February, mirror tests were performed with the FEL delivering 1.5 kW CW at 10 μm. The electron beam was at 3 mA. In March, low loss 6 μm optics were installed, and 9.1 mA of beam current was achieved, allowing the FEL to lase at 2.25 kW CW at that wavelength. In April, the third cryomodule was finally commissioned with an overall gradient of 86 MV, a more than factor of four improvement over the first modules made at JLab in the early 1990s. Meanwhile, the laser had achieved 4.1 kW CW for 15 minutes at a time with the beam at 7 mA.

[15] F. Dylla, "FEL Upgrade Project Overview Report for DoE/DoD Semi-Annual Review", presentation at 10 kW FEL Program Review, 29-30 January, 2004.

In May 2004, JLab shut down the FEL for three weeks to install the third cryomodule. When the machine came back on line, it readily achieved a higher beam energy of 145 MeV. For the events that followed, we return to JLab's weekly reports, and project manager Fred Dylla's announcement on 18 June, 2004:

> This is the week that Jefferson Lab's FEL Upgrade became a **10 kW class machine** [his emphasis throughout] and we established several new worlds records;
>
> - operating at duty cycles between 12 and 30%, the FEL produced **11.5 to 10 kW** of (macropulse) average power, respectively, infrared laser light at a 6 micron wavelength
> - operating at 48% duty cycle (8 ms pulses at 60Hz) the average power output was **8 kW**
> - operating at 100% duty cycle (cw), the average power was **6.2 kW**
>
> The machine was operated for more than a 2 hr continuous period during this high power demonstration, generating more than **18 MJoules** of output light. The measured parameters of the driver accelerator operating at 145 MeV and 4-5 mA were constant in terms of allowed energy and phase drift and compaction of the delivered electron beam to pulses within the wiggler as short as **420 fs**. FEL efficiencies of up to **1.7% (2.2kW/mA)** with energy recovery were demonstrated.[16]

In July of 2004, the laser reached 8.6 kW CW. Jefferson Lab was able to recirculate 9.1 mA of beam current indefinitely, a significant achievement in itself for an energy recovering linac. The only thing preventing extended 10 kW lasing was the combined effect of the high optical power and THz radiation on the optics.

[16] F. Dylla, "FEL Upgrade Project Weekly Brief - June 14-18, 2004", memorandum to distribution, 18 June, 2004.

Chapter 3

Technical Areas

We haven't the money so we've got to think.

—Lord Rutherford

This chapter contains a more in-depth look at various components of and phenomena related to free electron lasers, and the role played by each in the development of Jefferon Lab's 10 kW FEL. As mentioned in Section 1.1, the main components of a free electron laser are an *accelerator* and an *undulator*. Additionally, an *electron injector* is required as a source of electrons to be accelerated; some method of *beam transport* must be employed, particularly if the electron beam is to be recirculated; *optics* appropriate to the optical wavelength must be present in the form of oscillator mirrors (and elements of optical beam transport, if required); and adequate *diagnostics* to evaluate the performance of the machine. Each of these components is addressed in turn in this section.

Several physical characteristics or phenomena associated with free electron lasers are also addressed in this section: *coherent synchrotron radiation (CSR)*, which threatens electron beam quality at higher peak currents; *THz radiation*, initially a problem for the oscillator optics, but ultimately a welcome byproduct of electron beam recirculation; *space charge effects* which affect electron bunch shape inside the electron gun, and thus can impact beam quality; *beam break-up (BBU)*, a sort of feedback that occurs inside the accelerator cavities that can displace and affect the quality of the electron beam; the concepts of longitudinal and transverse *emittance*, measures of electron beam quality, the values of which are as important to control as electron beam energy and current; and *beam halo*, the current surrounding the electron beam, which will become significant for a beam near 1 A.

To complement the review of copious notes kept by JLab on their progress with each of the above components and characteristics, interviewees were asked to list what they perceived as lessons learned about each. The viewpoints of both ONR Review Panel members and JLab scientists were useful in providing perspective on often extremely detailed and specialized data. Some choice quotes are provided when appropriate.

The ONR Review Panel identified three major component-related issues impacting the Upgrade project:

- challenges in the development of an injector capable of producing both high beam current and beam quality,
- the beam break-up instability threshold in the third cryomodule,
- failure of optics and/or optical coatings to handle high power.

3.1 Electron Injector

The electron injector is a FEL's initial source of high energy ($\sim 10\,\mathrm{MeV}$) electrons. A pulsed drive laser photoelectrically liberates electrons from a highly charged cathode source. These electrons are accelerated, either by DC or RF fields, and directed into the linac. Based

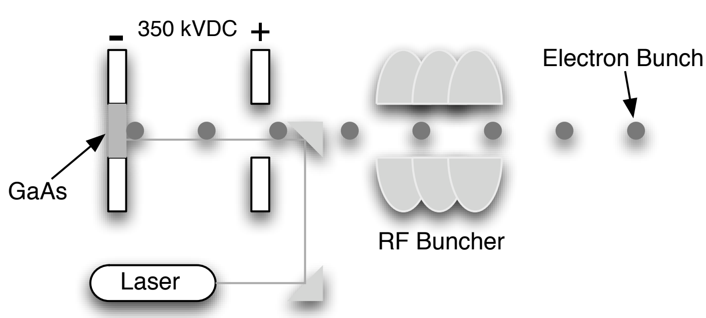

Figure 3.1: DC Photoinjector, the type used in the JLab FEL.

on the success of CEBAF's 200 μA DC injector, JLab developed a 5 mA DC gun for the IR Demo, in place when the Upgrade project began in June of 2000. Immediately, JLab began improving the gun cathode and discussing with vendors the modifications necessary to handle the higher current needed for the upgrade. Augmenting of the high voltage power supply (HVPS) was required to produce 10 mA at 350 kV, and some delay was incurred as JLab scientists advised the vendor as to how such augmenting might be achieved. The new HVPS was requested of the vendor in February of 2001 and received in June. Some additional modification of the HVPS was required upon delivery and performed by JLab technicians. In addition, a new tank to house the expanded HVPS was required. This was received in June of 2002, and the unit achieved 10.1 mA in October of 2002.

DC vs. RF Injectors

There are two main types of electron injectors: DC and RF. The RF injector category is further broken down into those injectors utilizing superconductor technology (SRF) and the traditional, room temperature RF.

In October 2002, an Injector Review Panel (a subpanel of the ONR Review Panel) presented a report to PMS-405 reviewing "potential injector technologies suitable for MW-class FEL operation". The report praised JLab's approach, while at the same time raising questions as to whether the technology was scalable to higher power. The report concluded that while there may be no scientific impediment to building a DC injector capable of producing the ~1 nC bunches required for MW lasing,

> it is the panel's sense that an SRF photoinjector **may** [their emphasis], in the long term, provide the best match to an FEL that uses SRF linacs.[1]

It was known that SRF injectors had the potential to outperform room temperature RF injectors, and it was thought that they might take up less space. On the other hand, SRF was as yet unproven, and development would take time. The report nonetheless encouraged JLab and industrial partner Advanced Energy Systems (AES) to continue work on DC injector technology, citing the demonstration of a nC-class DC gun as "fundamental to the down-selection of a MW class injector".

Space Charge Effects

In charged particle beams, the tendency of particles of like charge to repel each other results in degradations of beam quality known as space charge effects. An electron bunch is essentially a tightly packed "ball" of negative charges, and their mutual repulsion naturally affects bunch geometry over time. Longitudinal space charge (LSC) is alleviated by the rapid acceleration of electron bunches to relativistic speeds. Electrons traveling at nearly the speed of light are difficult to displace relative to each other, a quality known as "beam stiffness". Transversely, space charge effects tend to spread the beam, but this can be compensated for by focusing magnets in the beam transport lattice. It is a far simpler task to compress the bunch transversely than longitudinally.

At JLab, longitudinal space charge effects are observed at the injector where the beam energy is lower. The result is longitudinal emittance growth, which impacts the beam interaction in the FEL. Thus LSC effects are felt far downstream from their origin. JLab countered these effects by increasing the injected bunch length, thus reducing the peak current: less

[1] P. O'Shea, "Free Electron Laser High Brightness, High Average Current Injector Report", report to the Navy HEL Program Office (PMS-405) and Office of Naval Research, 28 October, 2002.

longitudinally dense bunches experience less longitudinal inter-electron repulsion. According to Dave Douglas, JLab's beam transport expert,

> this was an adequate workaround for the 10 kW machine, but cannot necessarily be construed as a solution applicable to all FEL's; if the bunch length is increased arbitrarily, the momentum spread after acceleration increases apace, and will eventually exceed the acceptance of the undulator.

Evidently, longitudinal space charge cannot be completely alleviated by increasing bunch length for arbitrarily high bunch charges.

Beam Halo

Beam halo describes the presence of extra charge outside the design parameters for the physical (transverse) extent of the electron beam. It is created when stray light from the injector drive laser hits extraneous regions of the cathode, generally out of phase with the scheduled pulses. The threat to FEL operation posed by stray electrons impacting the sides of the beam pipe is twofold: (1) it can cause harmful radiation, (2) it can compromise the vacuum. The non-catastrophic effect of halo is that the caution taken to limit it can also limit beam current.

Lessons Learned

Over the course of the 10 kW upgrade, Jefferson Lab made many improvements to their injector. During the last seven months of the project, JLab showed it was possible to

- anodize the unused portion of the cathode to minimize halo production,
- improve the vacuum isolation between the gun and the injector,
- improve the drive laser to reduce stray light, and
- recesiate[2] the cathode internally (without compromising the vacuum).

Along with other improvements, JLab was able to minimize commissioning time (days vice weeks without the improvements) and achieve higher voltage, reproducible recesiation, and ultimately 9.1 mA CW.

[2] Cesiation deposits a thin layer of cesium metal on the cathode, lowering its average work function and restoring quantum efficiency.

The path to a successful injector was far from painless, however. As previously mentioned, the electron gun voltage was a source of great debate between JLab and the ONR Review Panel. Panel members feared that the push for 500 kV in the gun would lead to arcing and breakdowns, and was not a Navy priority. Ultimately, the Panel recommended that the Navy restrict JLab from operating the gun over 350 kV. If a DC gun is to be used in a MW-class FEL, however, higher voltages must be achieved, and the advances JLab made in DC gun technology will benefit that effort.

3.2 Accelerator

> *Superconducting RF is impressive. JLab convinced me that superconducting accelerators are the future—not because of higher efficiency—but because of higher gradient.*
>
> —Charlie Brau, Vanderbilt University

Originally, it was JLab's expertise in accelerator technology that resulted in the construction of a high energy FEL. Cryogenic RF modules, pioneered by JLab for CEBAF, accelerate the electron beam to the energies required for lasing. Some Panel members commented on the limitations of using 1.5 GHz, a CEBAF legacy and not necessarily the best choice for an FEL. But by far the standout issue in the area of accelerators concerned the problems encountered with the third cryomodule. The debate over this piece of equipment is useful in illustrating the interdependencies of FEL components.

As per Equation 1.1, the relationship of the lasing wavelength λ to undulator period λ_0 and electron beam energy γ may be expressed

$$\lambda \propto \frac{\lambda_0}{\gamma^2}.$$

To lower the lasing wavelength one may either shorten the undulator period or raise the electron beam energy. In choosing the optical klystron, Jefferson Lab had committed to an undulator period that required more than the 80 MeV provided by the injector and first two cryomodules. More than one Panel member raised the notion of replacing the undulator, despite incumbent costs, but there was more to consider. According to JLab's Steve Benson,

> We could have designed a wiggler to get 1 micron with an 80 MeV beam but then we would not be able to lase at any longer wavelengths and would not be able to take advantage of the full design energy of the machine. The emittance requirement in that case is also even tighter and it is probable we would not have been able to reach it. With so many arguments against it we did not really consider such a design seriously.[3]

[3]S. Benson, Private Communication, 5 April, 2005.

Jefferson Lab had always envisioned a 150 MeV machine: emittance requirements are not as stringent (as mentioned above), and the FEL is more tunable at higher energies. More to the point, a lower energy electron beam would have to carry more charge per bunch into the undulator to achieve high power, and, as Benson puts it, the injector was "already being pushed pretty hard with 10 mA". Eventually, it was generally agreed that, given the limitations of the injector, 10 kW of 1 μm light could not have been extracted from the JLab FEL in its current configuration.

Nonetheless, there was disagreement as to how to proceed should the third cryomodule prove unusable. And there was continued concern expressed by Panel members over how such a critical flaw in the cryomodule could have occurred. Some Panel members remarked that the modules are fabricated by a JLab shop accustomed to the demands of CEBAF's electron beam which carries only μA of current.

Beam Break-up (BBU)

Beam break-up can occur during the acceleration of the electron beam within the cryomodules if the current throughput exceeds limits specific to the design of the accelerators. Electrons entering the accelerator can experience electric fields of higher order modes (HOM's) in the resonant RF cavities. These HOM's may then interact with subsequent electrons causing further deflection of the beam and eventual shutdown of the linac as the beam strikes the cavity wall.[4] Recirculating electron beams are particularly sensitive to BBU since electrons can re-enter the linac off-axis after transport, exacerbating the BBU condition.

Beam break-up was a topic of some concern and debate during the Upgrade. Jefferson Lab presented the 3rd cryomodule as necessary to reach the energies required for lasing at high power in the IR. As soon as postfabrication measurements were made, it was clear that the cryomodule did not meet the FEL group's specifications: the BBU threshold, expected to be 20 mA or higher, was actually $\sim$3 mA. It was bad news. The problem was identified as a misplacement of the HOM dampers: they were too far out in the beam pipe to couple to and effectively damp the BBU modes. Refrabication of the entire module would be necessary to change this, and that would take a year.

While some members of the panel shared JLab's confidence that BBU issues could be dealt with despite the flaw, others were concerned. While the challenge offered the opportunity to explore BBU physics, perhaps providing important experience for dealing with future higher-current beams (this did in fact turn out to be the case), the Panel felt it prudent to explore possible FEL configurations that might achieve 10 kW lasing at *any* wavelength. No such configurations were agreed upon.

[4] This document does not cover the safety system installed on the JLab FEL beamline. It incorporates devices which shut down the machine if high levels of radiation are detected outside the beam pipe. It is quite comprehensive, and an Occupational Safety and Health Administration (OSHA) review performed during the 10 kW Upgrade project produced a very favorable report.

Arranging to have the electrons, on their second pass through the cavity, not interact with the first pass mode.

Lessons Learned

The most obvious lesson learned is that superconducting RF cryomodules are getting better all the time. Ultimately, as the quote at the beginning of this section suggests, superconducting RF technology was indeed vindicated by JLab's production of a cryomodule with such a high gradient reaching 86 MV. Such economic use of real estate will be helpful in the eventual development of a compact free electron laser for use as a shipboard weapon.

Lessons were also learned in the deceleration of electrons and energy recovery. Induced energy spread from the undulator scales with extraction. There are varying opinions as to the ratio, but JLab recognized early the need to cope with sizeable ($\sim$10%) energy spreads. One way they addressed this need was the concept of asymmetric energy recovery, that is, purposefully recovering less than the maximum amount of energy from the recirculated beam.

Panel members were concerned that JLab knew about BBU issues with the third cryomodule long before they communicated them to the Panel. For their part, JLab was always confident that the issue might be resolved by any one of a few different commonly implemented methods, and did not perceive the low BBU threshold as a threat to the project. In fact, the performance of the third cryomodule was of less concern to JLab and to many Panel members as the questions it raised about the design of the FEL overall, as described above.

Disagreements aside, the events surrounding the incorporation of the cryomodule provide a good example of the role, other than oversight, played by the ONR Review Panel. Todd Smith of Stanford University made suggestions that proved instrumental in overcoming the unit's low BBU threshold.[5] There were other examples, but this one was commented on in almost every interview conducted. Jefferson Lab scientists, while inclined to point out that other solutions existed, tended to regard such interactions as the most useful role played by members of the Panel.

3.3 Transport

Two names came up in almost every interview conducted for this report: Todd Smith for his contribution to solving the BBU problem with the third cryomodule, and Jefferson Lab's Dave Douglas for his extraordinary beam transport system. While a few Panel members

[5] Smith suggested a modification to the beam transport arrangement that would prevent the electrons, on their second pass through the cavity, from interacting with the first pass mode.

remarked on its troubling cost—the system was identified as responsible for cost overruns in every phase of the project—all commented on the need for a robust, flexible beam transport system when building a prototype.

In addition to just getting the beam where it needs to go, the transport system is responsible for preserving the quality of the beam. Management of beam halo, preservation of longitudinal emittance, coping with coherent synchrotron radiation (CSR), and energy recovery each require unique arrangements of multipole electromagnets. And magnets and arrangements that work at certain energies do not always work at others. For example, as late as September 2003, the first arc (see Figure 3.2; a large format diagram of the 10 kW FEL is provided at the end of this report) of the beam line still employed a dipole used in the IR Demo which limited beam energy to 80 MeV. Sextupoles adapted from the 1 kW machine limited beam energy to 90 MeV until they were upgraded in early 2004.

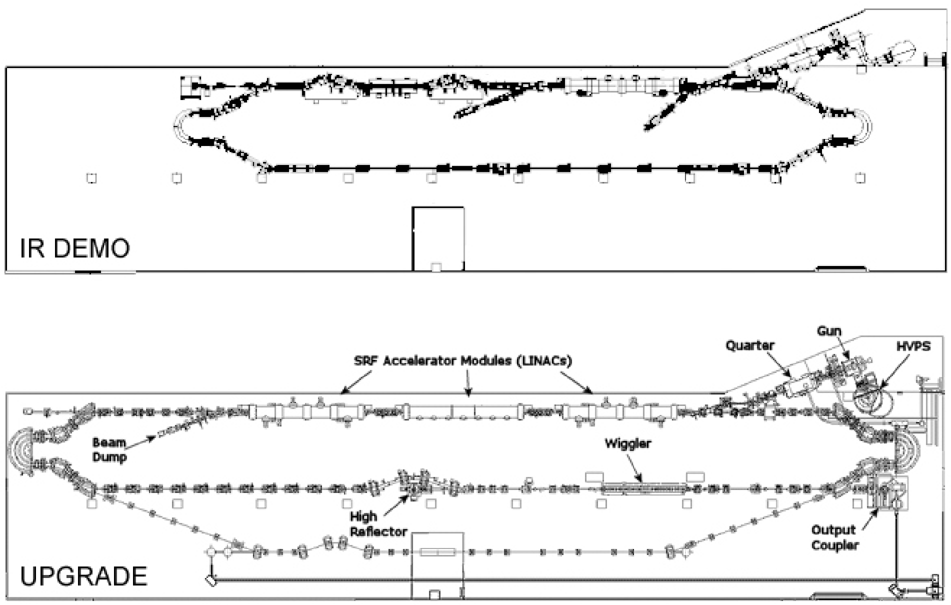

Figure 3.2: The IR Demo and 10 kW Upgrade. It is important to note that the 10 kW FEL's role as a demonstration device and physics test-bed contributes to its size. Jefferson Lab has concepts for more compact FEL's at 10 kW and higher, but the flexibility required of the beam transport system demanded more real estate. In other words: FEL's do not necessarily get bigger as they get more powerful.

It is the task of the transport system to preserve beam emittance. Emittance is the area occupied by the beam electrons in phase space and is an important measure of beam quality. The bunch profile in both transverse and longitudinal phase space is affected by accelerations felt by the bunch in the linac, in the undulator, and from every Lorentz push given the beam by over 180 steering and focusing magnets along its length. In general, longitudinal emittance, defined as bunch length times energy spread, was of greater concern for lasing than transverse emittance. For optimum extraction, as a bunch enters the undulator, the phase space distribution of its electrons resembles that shown in Figure 3.3a. Various effects felt by the beam throughout the FEL system, however, can lead to deviations from this ideal. Magnets along the transport system attempt to correct these deviations by variably accelerating and decelerating populations of electrons within the bunch.

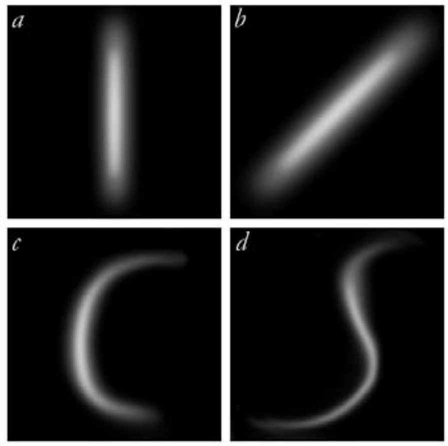

Figure 3.3: Electron phase space distributions. The ordinate is energy, the abscissa position. Ideally, electron bunches enter the undulator with the distribution shown in *a*. Linear corrections to distributions like *b* are effected by a quadrupole. A sextupole is required for quadratic corrections, as would be desired for distribution *c*. Third order corrections can, in principle, be made to distributions like *d* using an octupole.

Coherent Synchrotron Radiation (CSR)

For a long time, coherent synchrotron radiation (CSR) was thought to be a threat to high power recirculating FELs. The root of the problem is the same phenomenon that causes FEL's to lase in the first place: accelerating charges radiate. The bending of a recirculating electron beam necessarily accelerates the electrons as they turn corners, and they emit electromagnetic waves. Called synchrotron radiation, this light can be coherent when the bunch length is comparable to or shorter than the wavelength of the radiation being emitted, as it is in an FEL.

Proportional to the square of the number of emitting electrons, CSR is more brilliant than the regular, incoherent synchrotron radiation produced by longer bunches in traditional synchrotron light sources. The problem CSR presents to beam transport is the phenomenon of bunch self-interaction: the electrons in the bunch interact with radiation emitted by other electrons in the same bunch a moment earlier (see Figure 3.4).[6] The result is an

[6]Remember that the electrons are traveling at *nearly* the speed of light. This and the slight difference in path length—the electrons follow an arc, the photons follow a straight line—means that, in general, radiation from the tail of the bunch meets electrons at the head of the same bunch some time later.

increased energy spread among the electrons in that bunch. Electrons with different energies

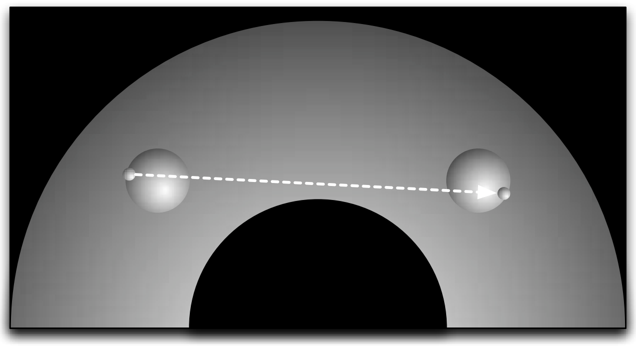

Figure 3.4: Bunch self-interaction via coherent synchrotron radiation. Radiation emitted from electrons at the tail of a bunch is absorbed a short time later by electrons at the head of the same bunch. The result is an increase in electron energy spread for that bunch.

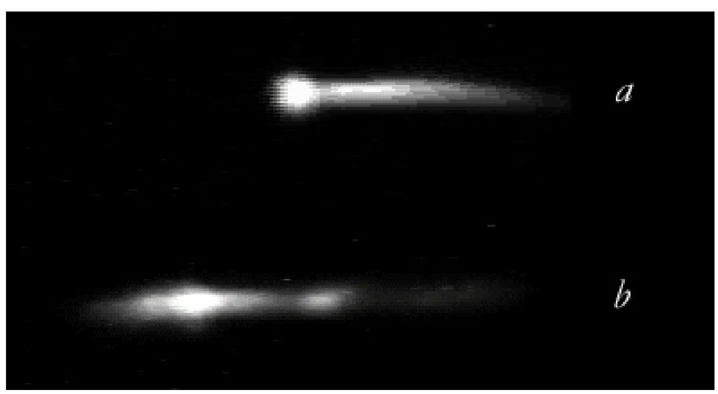

Figure 3.5: The effects of CSR on the electron beam. Image *a* is a head-on view of the beam after it rounds a bend from the left. Image *b* is a higher-current beam after the same bend. There is always a low-energy "tail" to the right (to the outside of the turn), but note the node-like structure reflecting charge density variations in the bunch and the displacement from beam path in *b*.

accelerate at different rates in a magnetic field, leading to a lateral dispersal of the beam as it rounds corner. There is always a "low-energy tail" after the beam is bent by a dipole, but the effects of CSR make for a dramatically disrupted beam, as shown in Figure 3.5 for a high-current beam. Free electron laser experts tend to agree that CSR has not been accurately modeled. More work is required connecting CSR modeling with experiment. This requires a detailed understanding understanding of the temporal shape of the beam (longitudinal profile), which requires high resolution diagnostics.

THz Radiation - A Digression

Identifying the sources of terahertz radiation in the Jefferson Lab free electron laser and methods of coping with it allows us to take a closer look at certain sections of the beam transport system.

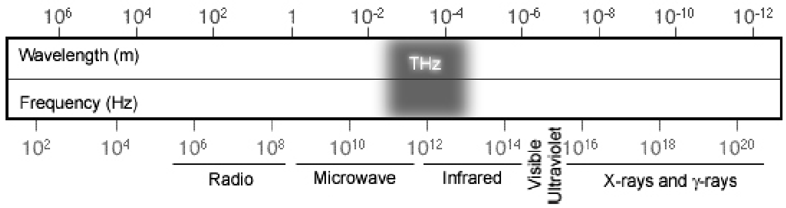

Figure 3.6: Terahertz radiation lies between the far infared and microwave ranges of the electromagnetic spectrum.

Common rhetoric in the field of terahertz radiation claims that this breed of light represents "the last unexplored frontier of the electromagnetic spectrum". The "terahertz gap", a name that alludes to a dirth of bright sources and sensitive detectors in this region, encompasses frequencies from 100 GHz up to roughly 30 THz (see Figure 3.6). Many common materials such as plastics, clothing, and living tissue are semi-transparent at these wavelengths, which, unlike X-rays, can be focused like visible light to produce sharp images. As a result, there is a great deal of interest in THz radiation from such diverse fields as medicine and homeland security.

Terahertz wavelengths are for the most part unreachable by microwave or laser sources. The oscillations required to produce THz light are too high frequency for typical radio circuitry, and the electronic transitions required for lasing in the terahertz range of 100 μm to 1 mm are so small (100 times smaller than those for visible light) that population inversions are difficult to achieve and maintain in all but the most advanced synthetic materials.[7]

While ultimately of great potential benefit to JLab, THz radiation continues to present a challenge to the FEL team. Although it is non-ionizing, THz light can heat components, and the component most affected was the oscillator outcoupler. Located just downstream of the first reverse bend dipole magnet (see Figure 3.7) this edge-cooled mirror, designed for limited absorption at the lasing wavelength (10 μm at the time), was being bombarded by terahertz light, heating it and causing it to deform. To work around the problem, JLab ultimately decided to swap the outcoupler and high reflector, which meant changing at which end of the oscillator laser light was emitted. The high reflector is back-plane cooled (in contact with chilled water over its entire rear surface—not possible with the outcoupler, which must transmit laser light) and is thus far more able to withstand the THz radiation

[7]Breakthroughs have been made using superlattices of semiconducting layers whose spacings effect artificial energy transitions, but so far these "quantum cascade" lasers are limited to ∼1 W.

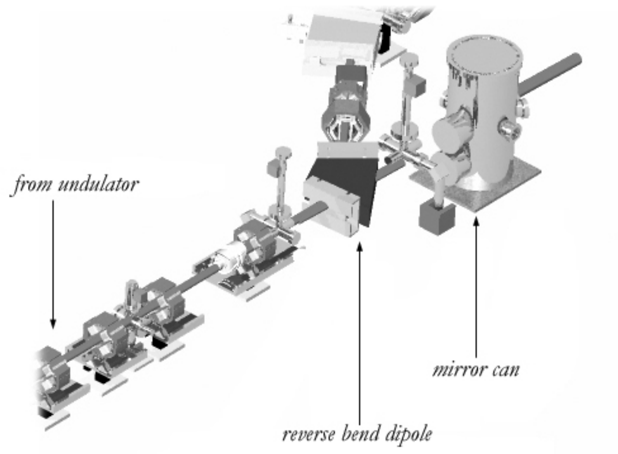

Figure 3.7: The source of problematic THz radiation. To varying degrees, all bends result in THz radiation, but at the first reverse bend dipole, this heating light shines directly on the downstream mirror of the oscillator.

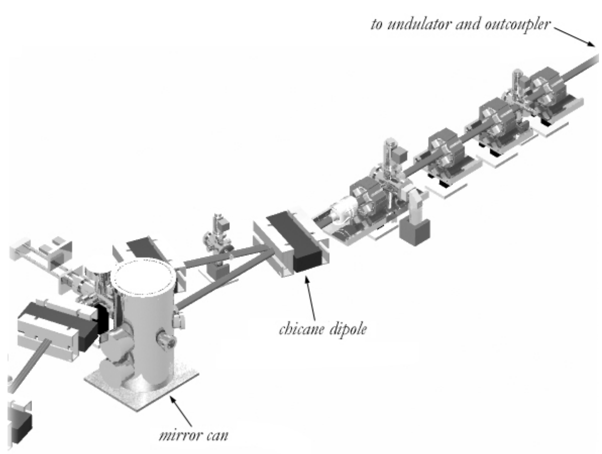

Figure 3.8: The source of useful THz radiation. Terahertz light is tapped from the chicane dipole just upstream of the undulator then transported up into the user facility.

without deforming. The fix worked, but in the future

> we plan to install a small chicane close to the wiggler that debunches the electron beam and reduces the THz edge emission to tolerable levels.[8]

Lessons Learned

The shorter bunches and higher charge of the 10 kW Upgrade introduced more coherent synchrotron radiation than its 1 kW precursor. It was found that "underbunching" the beam prior to it entering the undulator (that is, intentionally not achieving the minimum possible bunch length) greatly reduced CSR that was impacting energy recovery.

On the subject of space charge (discussed in Section 3.1), while workarounds exist, according to Dave Douglas

> Longitudinal space charge remains a monumental challenge to the production of appropriately configured beams at the wiggler. An adequate program of simulations including this effect is *essential* [his emphasis] to system design for future machines.[9]

Another clear lesson is that energy recovering linacs benefit greatly from the use of high quality magnet power supplies, which can be a sizeable investment, but will pay off during operation.

[8] S. Benson, et al., "High Power Lasing in the IR Upgrade FEL at Jefferson Lab", *XXVI International FEL Conference Proceedings*, August, 2004.

[9] D. Douglas, Private Communication, 14 April, 2005.

During interviews, scientists at JLab as well as many members of the ONR Review Panel characterized THz radiation in the JLab FEL as an important observation. Some Panel members alluded to it as an example of a welcome byproduct of Navy-sponsored scientific research whose continued investigation, while not directly in line with programmatic goals, should be not only tolerated but encouraged. Exploiting such discoveries benefits FEL research in general and lends credibility to a project in the scientific community. Indeed, in November of 2001, JLab broke world records with the production of 100 W of broadband THz radiation. The source was a dipole magnet used to direct the electron beam into the undulator after steering around the upstream mirror can (see Figure 3.8). The THz light was directed out of the beamline and up into the user facility where experimenters could make use of it.[10]

Terahertz radiation will probably be of great concern in a megawatt class free electron laser. Care will have to be taken in anticipating and controlling the effects of electron beam bends generating as much as a kilowatt of broadband THz light.

3.4 Undulator

The extent to which an operating FEL is tunable and over what range of wavelengths depends primarily on the undulator. It is the period at which transverse oscillations in the electron beam are induced that determines the wavelength of emitted light, thus the periodic spacing of the undulator magnets ultimately dictates what range of frequencies correspond to a given range of electron beam energies.

Lessons Learned

The undulator is the most mature of FEL technologies. Experiments with taper (a linear or nonlinear variation in magnetic field strength along the length of the undulator) and different undulator geometries continue at FEL's around the world, but undulator physics is largely regarded as a known quantity. Simulations at higher beam currents ($\sim$1 A) do not indicate significant deviation from present performance.

While everyone agrees the optical klystron undulator was not the optimum undulator for the 10 kW upgrade, it was not without its advantages. The dispersive section in the center of the undulator allows reshaping of the bunch to improve gain. Also, the ability exists to vary the number of effective periods and actually adjust the FEL parameter K by varying current through the undulator, impossible with a permanent magnet undulator. However,

[10] The details of the THz studies at JLab are beyond the scope of this document, but the story is one well deserving of attention as it may shed light on the dynamics of the research group as they relate to the funding profile and both project and institutional management.

it was generally perceived as a necessary compromise. According to Steve Benson,

> If one wants a wiggler optimized for a 150 MeV accelerator that can tune from 1.05 to 2.2 microns (covering all the water windows in the near-infrared) a good compromise between tuning range, gain, and gap is a 5-6 cm wiggler period.

Constrained by budget, and having been repeatedly admonished by the Navy to cut costs, JLab elected to use the donated undulator.[11] Some Panel members continue to speculate that JLab might have reached 1 μm with a 3 cm undulator and an 80 MeV beam, but not at 10 kW power.

3.5 Optics

An oscillator FEL requires the highest quality optics with very low absorption in the operating wavelength. Unlike solid state or chemical lasers of similar power, FEL's operate in the fundamental optical mode, concentrating light intensity directly into the center of cavity optics. This can cause distortion if the optics, their coatings, or their mounts absorb too much power. And unlike amplifier FEL's, distorted optics can restrict lasing power by affecting gain.

Trying for 10 kW lasing at 10 μm was motivated by the fact that, for a given electron beam energy and quality, extraction is higher and thus it is easier to lase at longer wavelengths. Jefferson Lab estimated that such power was attainable if a 10 μm outcoupler could be fabricated with losses under 500 ppm. The best the vendors could do was a *possible* 800 ppm, and some of the 10 μm optics JLab received actually measured losses a factor of ten higher than that. Such large absorption led to rapid growth of optical aberrations. By January 2004, JLab had all but eliminated the idea of 10 kW lasing at 10 μm. High power would ultimately be achieved at 6 μm.

Lessons Learned

Obtaining high power optics appears to have been one of the greatest challenges for JLab during this project. Some panel members felt there was more JLab could have done to procure higher quality optics and coatings, or that experts in the field had not been consulted. For her part, JLab optics chief Michelle Shinn was in constant contact with Panel chairman John Albertine and consulted experts from the Boeing Corporation and Naval Air Warfare Center Weapons Division, China Lake. Even so, she candidly admits to a lesson learned:

[11] The optical klystron was not exactly *free*, but it was close. It was built to JLab specifications, and represents a considerable contribution to the project by Northrop Grumman.

> Make no assumptions on optics: the literature exists, as do experts (if you dig deeply enough). High loss at 10.6 micron optics was unanticipated. Literature existed that verified this.

Some Panel members felt it was poor judgment to continue to spend money on efforts for high power (like the third cryomodule and transport for higher beam energies) when mirror heating had already been shown to be a problem, even at low power. While several interviewees expressed sentiments along these lines, it appears to be an oversimplification to cast FEL procurement priorities as competing for funds. Also, Jefferson Lab made no attempt to characterize optics failures at longer wavelengths as a *justification* for including the third cryomodule, maintaining that 150 MeV was the baseline for this laser, whatever the ultimate lasing wavelength.

As with the transport system, the critical role played by vendors in the field of optics cannot be overstated. The quality of optics required by JLab exceeds the abilities of the optics industry to measure, and suppliers of optics contract with JLab on a "best-efforts" basis. Vendors will generally specify the quality of optics within the limits of their instrumentation, but cannot guarantee, for example, absorption levels—a critical issue for resonator optics. For their part, vendors tended to truly exhibit best-efforts, delivering ahead of schedule when possible and at times replacing flawed or lossy optics at no additional cost.

In addition to concerns with handling radiation that was going where it was supposed to, losses in the optical cavity caused problems as well. As cautionary a tale as can be told, JLab neatly summed up their experiences with stray high power light:

> When lasing at 5.75 microns and 10 kW the output coupling was 8%. This means that the circulating power exceeded 125 kW. Even scatter of parts per thousand can lead to major problems in the cavity. We found that the rings holding the mirrors tended to heat after a time running at high power. This lead [*sic*] to changes in the mirror alignment cavity length. We had planned to use a helium-neon laser to track the mirror angle. Scattered light absorbed in the windows for this system distorted them sufficiently so that this was not possible. When we tried to shield the windows with metal screens we found that the scattered light melted holes in them. THz light also heated beamline elements and led to vacuum rises and optical distortion. Clearly, high power laser systems have to account for all power losses in the system and must be shielded from spurious light of all wavelengths.[12]

When contrasting FEL's with other types of lasers that contain vulnerable lasing media, it is a somewhat equalizing notion that at higher powers the optics, their supports, the beam tube—the very structure of the machine itself becomes vulnerable.

[12] Benson, 2004.

3.6 Diagnostics

> *Diagnostics pay for themselves. However much a diagnostic device costs, it is cheap.*
>
> —George Neil, JLab

As of January, 2004, the following diagnostic equipment was in place along the electron beam transport system:

- 30 beam profile monitors (BPM),
- 28 beam viewers,
- 6 synchrotron light monitors (SLM),
- a phase-transfer function measurement system,
- a Happek bunch-length monitor (extracts and analyzes synchrotron radiation),

as well as the entire THz subsystem, itself a useful diagnostic tool and high-fidelity indicator of electron beam performance. The vigilant analysis of diagnostic feedback and the redundancy between diagnostic tools meant that the beam line was well instrumented, with the possible exception of the injector itself. While cost played a role in this, there was more to consider. Jefferson Lab's George Neil provided an explanation:

> [The injector's] setup and operation is made difficult because a) diagnostics are difficult at low energy; measurements are affected by space charge more there and viewers give off less light, and b) to get the best performance it is essential to keep the beamline compact; this directly conflicts with the need to have more diagnostics in the line. We have 33 free parameters to adjust in the front end and only about 6 measurements that we can perform. That leaves the operator having to infer settings from how the beam behaves when you change things as well as compare performance to models.[13]

From the beginning of the project, JLab advocated the funding of an injector test stand: a separately and independently run duplicate of the injector system:

> One way to improve beam setup (as well as end up with a backup system in case of component failures) is to have a separate injector system with lots of diagnostics on it used to validate computer models and establish correct settings and dependencies which can then be transferred over to the operational system. Since such a test stand is not subject to the same space or operational constraints as an injector on the real machine it can be a very efficient way to optimize the system.[14]

[13] G. Neil, Private Communication, 11 April, 2005.
[14] *Ibid.*

Lessons Learned

Panel members agreed: you cannot have too many diagnostics. Strongly advocated was the use of 6-dimensional phase space beam profile monitors as soon as the technology is developed and available (work is being done on this at SLAC and Brookhaven National Laboratory (BNL)). One Panel member thought JLab had not installed as many diagnostics as were possible. Most recognized the space constraints of the FEL hall at JLab. One specific suggestion was the idea of a sliding electron gun, one that could be backed away from the injector and fit with analytic tools, that is, an *in situ* gun test stand. One diagnostic tool JLab would have liked very much to have purchased was a ($400,000.00) streak camera, a high speed light detector.

Chapter 4

Conclusion

> *An expert is a man who has made all the mistakes which can be made in a very narrow field.*
>
> *—Niels Bohr*

Jefferson Lab now possesses the most powerful free electron laser in the world. As a result, the members of the FEL group at JLab now lead their field, and others come to them for advice. Around the world, at least eight other energy recovering linac FEL's are under construction based on JLab's design. One JLab scientist complained

> It's frustrating: I'll do a search [in the literature] for a particular FEL issue, and the only search results I get back are JLab papers.

As JLab continues work on the FEL, now with a more secure budget and a great deal of success under their belts, they proceed as pioneers, acknowledged by every ONR Review Panel member as competent, hard-working, passionate scientists. Despite this, Panel members were universally inclined to caution against arrogance and over-optimism, and to encourage JLab to seek and accept outside help when needed.

In hindsight, some of the setbacks during the Jefferson Lab IR Demo Upgrade project might have been avoided. But such perspective is remote from the day to day operations of a lab engaged in pushing the limits of a technology, on a very tight budget, with very little margin for error. There were times during 2003 that JLab was funded almost on a week to week basis. This coincided with some of the most challenging and labor-intensive portions of the Upgrade involving 14 to 18 hour days for many key personnel. In the face of this, the FEL group at JLab impressed many with their lean and hungry approach to science.

An overarching lesson learned is that the 25% contingency that sometimes exists in the research budget for such large projects—but did not exist for the 10 kW upgrade—would have been of great benefit to JLab. For a fixed cost, goals or schedules may need to be adjusted to provide such a contingency. Extra funds, had they been available, would not have been squandered at JLab. A contingency would have sped up the project by mitigating setbacks encountered with technologies considered potentially expedient, but ultimately dismissed as high-risk.

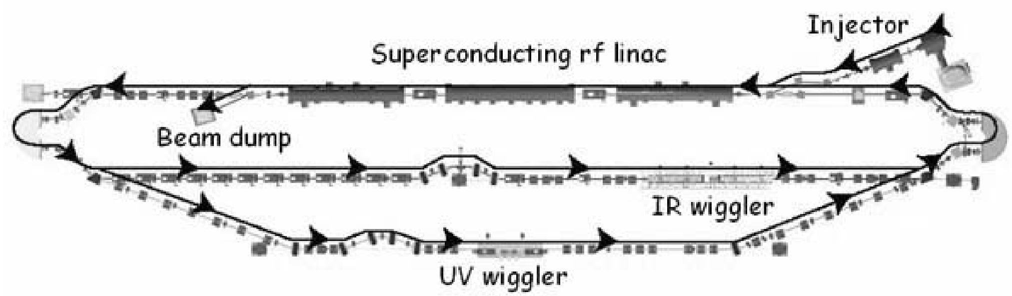

Figure 4.1: The free electron laser as shown on the JLab website, April 2005.

On the Jefferson Lab website, one finds the specifications for the free electron laser as shown in Table 4.1.

Table 4.1: JLab FEL Parameters, April 2005

Output Light Parameters	
Wavelength range (μm)	1.4 - 14
Bunch length, FWHM (ps)	0.2 - 2
Laser power / pulse (μJ)	67
Laser power (kW)	5
Repetition rate, CW operation (MHz)	40

Electron Beam Parameters	
Energy (MeV)	80-200
Charge per bunch (pC)	135
Average current (mA)	10
Peak current (A)	270
Beam power (kW)	2000
Energy spread (%)	0.50
Normalized emittance (mm-mrad)	<30
Induced energy spread, full (%)	10

Source: http://www.jlab.org/FEL/felspecs.html, April 2005.

Referring back to Table 2.2, the parameters specified in the original plan for the IR Demo Upgrade are nearly all met. Some Panel members feel it is important to emphasize the considerable achievement of 10 mA average current, and that the 5 kW CW reported above

Table 4.2: 100 kW FEL Specifications, Notional

Proposed 100 kW FEL Parameters	
Wavelength range (μm)	1 - 1.6
Laser power (kW)	100
Energy (MeV)	100 - 200
Accelerator frequency (MHz)	750
Average current (mA)	100
Cavity length (m)	16 - 24
Undulator length (m)	1
Undulator period (cm)	3

Source: JLab.

is certainly conservative—the JLab FEL has lased at 8.6 kW CW, and at 10 kW for one second intervals. Again, the limiting factor is optics.

When asked for notional parameters for a 100 kW FEL (the acknowledged next step to a weapon-class laser), Steve Benson gave the numbers shown in Table 4.2. It is general opinion among the ONR Review Panel that private industry must play a significant role in the construction of the next-order-of-magnitude FEL, but it is to the experts at JLab that industry will likely be turning to figure out how.

Bibliography

Jackson, J. D. *Classical Electrodynamics*. Wiley, New York, 1999.

Pedrotti, F. L. and Pedrotti, L. S. *Introduction to Optics*. Prentice Hall, Upper Saddle River, New Jersey, 1993.

Rosenzweig, J. B. *Fundamentals of Beam Physics*. Oxford University Press, Oxford, 2003.

As of this writing (April 2005), the Jefferon Lab weekly briefs cited herein may be found at: http://www.jlab.org/FEL/felpubs/.

INITIAL DISTRIBUTION LIST

1.	Defense Technical Information Center 8725 John J. Kingman Road, STE 0944 Fort Belvoir, VA 22060-6218	2
2.	Dudley Knox Library, Code 013 Naval Postgraduate School Monterey, CA 93943-5100	2
3.	CAPT Roger McGinnis, USN NAVSEA PMS-405 WNY Bldg. 197 2W 2916 MS 5013 Washington, DC 20376-5013	3
4.	CDR Scott Nessler, USN NAVSEA PMS-405 WNY Bldg. 197 2W 3256 MS 5013 Washington, DC 20376-5013	1
5.	Gene Nolting NAVSEA PMS-405 WNY Bldg. 197 2W3256 MS 5013 Washington, DC 20376-5013	1
6.	Quentin Saulter Office of Naval Research, BCT1 800 North Quincy Street Arlington, VA 22217-5660	3
7.	Gil Graff Office of Naval Research 800 North Quincy Street Arlington, VA 22217	1
8.	Michael Deitchman Office of Naval Research 2129 Darcy Green Place Silver Spring, MD 20910	1
9.	Fred Dylla Jefferson Lab 1200 Jefferson Avenue Newport News, VA 23607	3

10. George Neil 1
Jefferson Lab
1200 Jefferson Avenue
Newport News, VA 23607

11. Michelle Shinn 1
Jefferson Lab
1200 Jefferson Avenue
Newport News, VA 23607

12. Dave Douglas 1
Jefferson Lab
1200 Jefferson Avenue
Newport News, VA 23607

13. Steve Benson 1
Jefferson Lab
1200 Jefferson Avenue
Newport News, VA 23607

14. Kevin Jordan 1
Jefferson Lab
1200 Jefferson Avenue
Newport News, VA 23607

15. John Albertine 1
109 Kingswood Road
Annapolis, MD 21401

16. Alan Todd 1
Advanced Energy Systems
P. O. Box 7455
Pinceton, NJ 08543-7455

17. Patrick O'Shea 1
University of Maryland
IREAP
College Park, MD 20741-3511

18. Henry Freund 1
SAIC/NRL
1710 SAIC Drive
Mclean, VA 22102

19. Charles Brau 1
Vanderbilt University - Physics Department
Box 1807 B
Nachville, TN 37235

20. Dinh Nguyen 1
Los Alamos National Lab
MS H-851
Los Alamos, NM 87545

21. Richard Sheffield 1
Los Alamos National Lab
LANSCE-1, MS H-928
Los Alamos, NM 87545

22. Mike Fazio 1
Los Alamos National Lab
MS H-851
Los Alamos, NM 87545

23. Dan Prono 1
Los Alamos National Lab
Dynamics Testing Division, MS F-613
Los Alamos, NM 87545

24. Todd Smith 1
Stanford University
Hansen Experimental Research Lab
Stanford, CA 94305

25. Dave Dowell 1
Stanford Linear Accelerator Center
2575 Sand Hill Road
Menlo Park, CA 94025

26. Tom Hodge 1
HELSTF
US Highway 70, Mile Marker 186
White Sands, NM 88002

27. Fred Marcell 1
Schafer Corporation
2309 Renard Place SE, Suite 300
Albuquerque, NM 87106

28. Jack Slater 1
Schafer Corporation
2309 Renard Place SE, Suite 300
Albuquerque, NM 87106

29. Rich Nguyen 1
Joint Technology Office
901 University Boulevard SE
Albuquerque, NM 87106

30. Sandra Biedron 1
Argonne National Lab - Energy Systems Division
9700 South Cass Avenue, Building 200 C-157
Argonne, IL 60643

31. John Lewellen 1
Argonne National Lab
9700 South Cass Avenue, 401/B2190
Argonne, IL 60639

32. James Mulroy 1
Missile Defense Agency
1107 Archer Court
Alexandria, VA 22312

33. Keith Lyles 1
Noesis
4100 North Fairfax Drive, Suite 800
Arlington, VA 22203-1663

34. Alfred Skolnick 1
System Science Consultants
5432 North Carlin Springs Road
Arlington, VA 22203-1202

35. Mark Litz 1
Army Research Lab
2800 Powder Mill Road
Adelphi, MD 20783

36. Kevin Jensen 1
Naval Research Lab
4555 Overlook Avenue
Washington, DC 20375-5347

37. Phil Sprangle 1
Naval Research Lab
4555 Overlook Avenue
Washington, DC 20375-5347

38. Baruch Levush 1
Naval Research Lab
4555 Overlook Avenue
Washington, DC 20375-5347

39. Ilan Ben-Zvi 1
Brookhaven National Lab
MS 911B
Upton, NY 11973-5000

40. James Murphy 1
Brookhaven National Lab
MS 911B
Upton, NY 11973-5000